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Radio Techniques for Probing the Terrestrial Ionosphere

With 152 Figures

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This monograph
is dedicated to
my wife Phyllis

Preface

In the years since the pioneering efforts of Sir Edward Appleton, M. A. F. Barnett, G. Breit, and M. A. Tuve, many radio techniques have been employed to investigate the terrestrial ionosphere. The purposes of this book are to examine the basic physical interaction process of radio waves with the ionosphere, scrutinize each of the radio techniques currently in use, and describe the elements of each technique, as well as assess their capabilities and limitations. I have included some of the history of each technique, since we often tend to forget the efforts of the "pioneers".

The interaction of radio waves with the terrestrial ionosphere has been described in considerable detail in several "classic" treatments, e.g., Ratcliffe (1959), Al'pert (1963), Budden (1961) and Davies (1965), Rishbeth and Garriott (1969), and in other more recent books, e.g., Flock (1979), Davies (1990), Hargreaves (1979), and Budden (1985). A few of the radio techniques have been described by Hargreaves (1979) and a book by Giraud and Petit (1978) has also included discussion of several of the techniques. The "WITS" handbook No. 2 (1989) also contains description of several radio techniques.

This book is primarily addressed to graduate students and beginning researchers in aeronomy, and hopefully, will also serve as a compendium for active workers in the field. It is hoped that the book will aid researchers in aeronomy and ionospheric propagation to gain an appreciation of "how radio techniques work", and describe the information one can expect to obtain from each particular technique. More specifically, the author has attempted to objectively appraise in some detail the capabilities and limitations of each particular radio technique. The "limitations" sections will probably result in "stepping on the toes" of the proponents of certain techniques, who are convinced that their particular method tells the "absolute truth" at the greatest efficiency and in a most elegant manner about the peculiar ionospheric pathogen which they are studying! One is sometimes reminded of the well-known Indian proverb about the "blind men and the elephant", wherein each of the men is certain that the particular portion of the beast he has grasped reveals the entire truth and the complete description of the pachyderm! Some of the material in this book is based on a course *Experimental Methods in Aeronomy and Space Physics* offered to graduate students at the University of Alaska. I am indebted to these students for valuable mutual exchange of ideas throughout the years. As many Professors discover, some of their best colleagues have been their students.

I believe that the timing of this volume is fortuitous for the following reasons: (1) radio techniques have, indeed, been utilized to study the terrestrial ionosphere for some 65 years now, and the passing decades have seen the elimination of a few techniques, the modification of some, the introduction of several new ones, and the persistence of some (such as the ionosonde). (2) The era of international research cooperations such as the International Geophysical Year (IGY) and following intervals was particularly dynamic for the development of new techniques and the refinement of others. (3) Likewise, the decade of the 1980's witnessed the worldwide deployment of several sophisticated systems (incoherent scatter radars, coherent VHF and HF Doppler radars, and satellite beacon systems); some of these systems and "first results" are described in special issues of the journals *Radio Science* (vol. 18, 1983), Greenwald and Hunsucker (1983), *Journal of Atmospheric and Terrestrial Physics* (vol. 46, 1984), and *Geophyiscal Research Letters* (vol. 11, 1984).

Before proceeding further, the reader should realize that the research area described by the title of this book is cursed with many acronyms, abbreviations, and nonstandardized symbols. Appendices A.1 and A.2 are provided in an attempt to alleviate this "alphabet-soup" problem. Similarly, when one is confronted with all the pathogenic problems of implementing a sophisticated radio technique at some of the hostile field sites of interest to ionospheric physicists, there is no one book which will provide all the solutions. This book is no exception. It is my hope, however, that the material in this monograph will at least provide a glimpse of the path to follow toward the partial solution of some problems, as well as describe the specific radio instrumentation techniques used by ionospheric physicists.

Before listing my acknowledgements for this book, I would like to give a salute to the scientists and engineers who actually *invented* these techniques! I would like to express my sincere appreciation to several people who helped to make this book possible. Two successive directors of the Geophysical Institute of the University of Alaska, Juan Roederer and Syun-Ichi Akasofu, offered considerable encouragement and financial support when most needed. Other colleagues at the Geophysical Institute, in particular Brenton Watkins, Paul Johnston, and Brett Delana reviewed parts of the book, as did graduate students Donald Rice and Ning Jing. Louis Lanzerotti of AT & T Bell Laboratories suggested that a book on *Techniques* should be written for this series, and invited me to attempt the project while I was working with him during sabbatical leave. He has been a constant source of encouragement. I am also indebted to a host of friends and colleagues I have had the pleasure of knowing and working with during the last three decades. They have reviewed each of my chapters as they were finished. In particular, Robert Benson of the NASA Goddard Space Flight Center, Richard Behnke of the National Science Foundation, Thomas Croft, then at SRI-I, Kenneth Davies of the NOAA Space Environmental Labs, Louis Duncan of Clemson University, Tony Ferraro of Penn State University, Warren Flock of the University of Colorado (who was also chairman of my Ph. D. committee), Ray Greenwald of the Johns Hopkins Applied Physics Lab, Dick Grubb of NOAA Space Environment Labs, John

Hargreaves of the University of Lancaster, Robert Helliwell of Stanford University, O. G. (Mike) Villard of Stanford University, and last (but certainly not least) Jim Wait of the University of Arizona. I would also be remiss if I did not acknowledge the support and encouragement from the Electrical Engineering Department of the University of Alaska Fairbanks. Specifically, thanks are due to Vince Haneman, Dean of the School of Engineering and to John Aspnes, Chairman of the Electrical Engineering Department, also to Robert Merritt and Thomas Roberts for stimulating discussions. Finally, my sincere thanks to Vickie Ivester and Debbie LaBarre for their painstaking and accurate preparation of the final version of the manuscript.

ROBERT D. HUNSUCKER

Contents

Part I Introduction

The use of radio waves to explore the terrestrial atmosphere began with the pioneering efforts of Appleton and Barnett (1926) and Breit and Tuve (1926), when they independently used different techniques to detect ionospheric layers. Their work was, of course, founded on Marconi's demonstration of transatlantic radio transmissions and on the hypotheses of Kennelly (1902) and Heaviside (1902), who independently concluded that there must be radio-reflecting layers in the upper atmosphere to explain certain experimental results. The foregoing discoveries rested upon the bedrock of the experimental and theoretical work of Heinrich Hertz (1893) and James Clerk-Maxwell (1873) respectively. The references at the end of this book include some of the salient articles describing the experimental and theoretical work mentioned above. Additional descriptions of historical development of the specific techniques and of the theory will be found in various sections of this book, and an excellent historical account of the origins of radio from Hertz into the 1920's may be found in two volumes by Aitken (1985a, b).

As mentioned in the Preface, it is assumed that the users of this book have studied electromagnetic theory at least at the undergraduate level and have a reasonable understanding of the principles of the generation of EM waves, their propagation in free space, transmission lines and waveguides, and basic antenna theory. Those who feel the need for a review of these topics will find ample material in the textbooks by Jordan and Balmain (1968), Ramo et al. (1965), Sander and Reed (1986), Kraus (1988), and Wait (1985). Researchers seeking specific information on radio engineering and antenna design should also find the annotated bibliography a useful starting point.

An essential lesson learned by the successful "journeyman ionospheric physicist of the experimental persuasion" in order to design the appropriate experiment is that he (or she) must know the basic ionospheric parameters and their expected variance which describe the particular ionospheric phenomenon to be studied. It is hoped that this book may be of some help in that task – particularly in the selection of the best technique or techniques.

The "road map" for this book starts in Chapter 1 with an outline of the structure and nomenclature of the earth's neutral atmosphere and ionosphere showing some "typical" and a few atypical features, including representative electron density profiles illustrating the high variance encountered. This is followed by a mathematical and physical description of the basic properties of electromagnetic waves propagating in free space and in other media and concluded by a discussion of the radar equation. Chapter 2 concerns the behavior of radio waves in the ionosphere and includes the elements of magnetoionic theory and incoherent scatter theory. The basic effects of the ionosphere upon a radio wave which "intrudes in its domain" – such as reflection, refraction, diffraction, scattering, attenuation, and changes in polarization – are discussed.

The remaining chapters examine each of the "generic" radio techniques used by ionospheric physicists to explore the terrestrial ionosphere remotely. Chapters 8 and 9 include discussions of in-situ ionospheric probing systems utilized in rockets and satellites as well as various radio techniques, and Chapter 10 is a summary of this monograph with concluding remarks.

Chapter 1 Terrestrial Atmospheric Structure and Properties of Electromagnetic Waves

Scanning the terrain of Chapter 1 reveals a somewhat "lumpy topography" wherein we discuss some diverse topics including the radio spectrum, atmospheric structure and composition, electrical noise, fundamental properties of electromagnetic waves, and the radar equation, in that order. A logical starting point, then, seems to be a short discussion of the electromagnetic spectrum in general and that particular region of the spectrum employed for ionospheric studies.

1.1 The Radio Spectrum

In general, the portion of the electromagnetic spectrum utilized to investigate the ionosphere of the earth includes approximately 10 kHz through 1300 MHz, or VLF-UHF (for acronyms see Appendix A.2). Figure 1.1 may be of use in visualizing the frequency spectrum used for the radio techniques described in this book. A more detailed spectrum chart is provided in Appendix A.3, including the International Telecommunications Union (ITU) band nomenclature, some of the international frequency band allocations, and other information useful to radio engineers.

1.2 Structure and Composition of the Terrestrial Ionosphere

Before proceeding with an abbreviated account of the details of EM wave interaction with the terrestrial ionosphere in Chapter 2, we will briefly describe the basic structure and properties of the terrestrial atmosphere. Figure 1.2 shows a schematic representation of the earth's atmosphere under rather idealized conditions, including the height variation of temperature, as well as standard atmospheric nomenclature and other properties. A more detailed description of the daytime electron density distribution versus height is shown in Fig. 1.3. The ionospheric layer nomenclature along with a qualitative picture of ionospheric radio propagation mode structure and penetration levels of solar radiation are also illustrated. Further details on the properties and pertinent physical and chemical parameters of the specific ionospheric layers are shown in Table 1.1. Physical and mathematical descriptions of the very complex processes and dynamics of the ionosphere are thoroughly covered in standard texts and monographs, e.g., Banks and Kockarts (1973), Bauer (1973), Kato (1980), Gurevitch (1978), Chamberlain (1978), and Rees (1989).

RADIO TECHNIQUES FOR PROBING THE IONOSPHERE

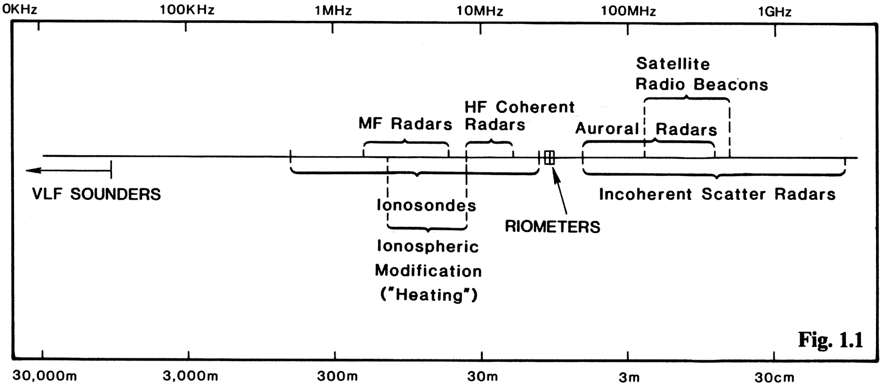


Fig. 1.1

FREE-SPACE WAVELENGTH (λ_o)

ATMOSPHERE

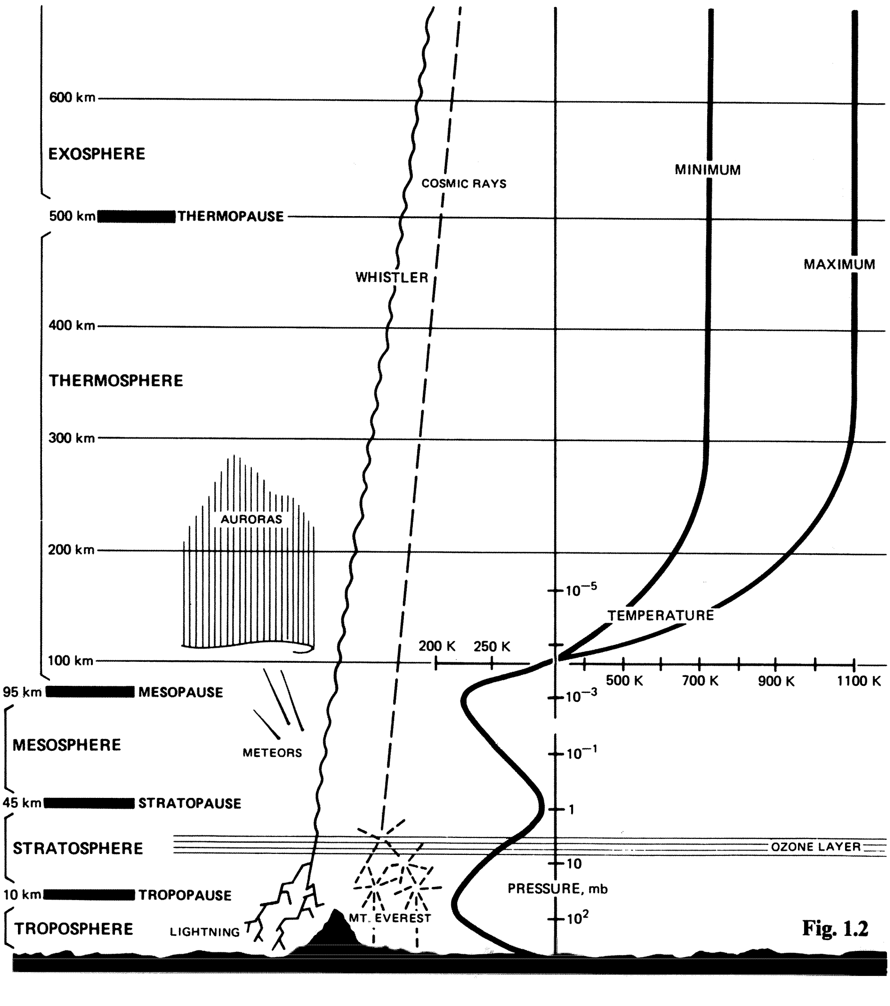


Fig. 1.2

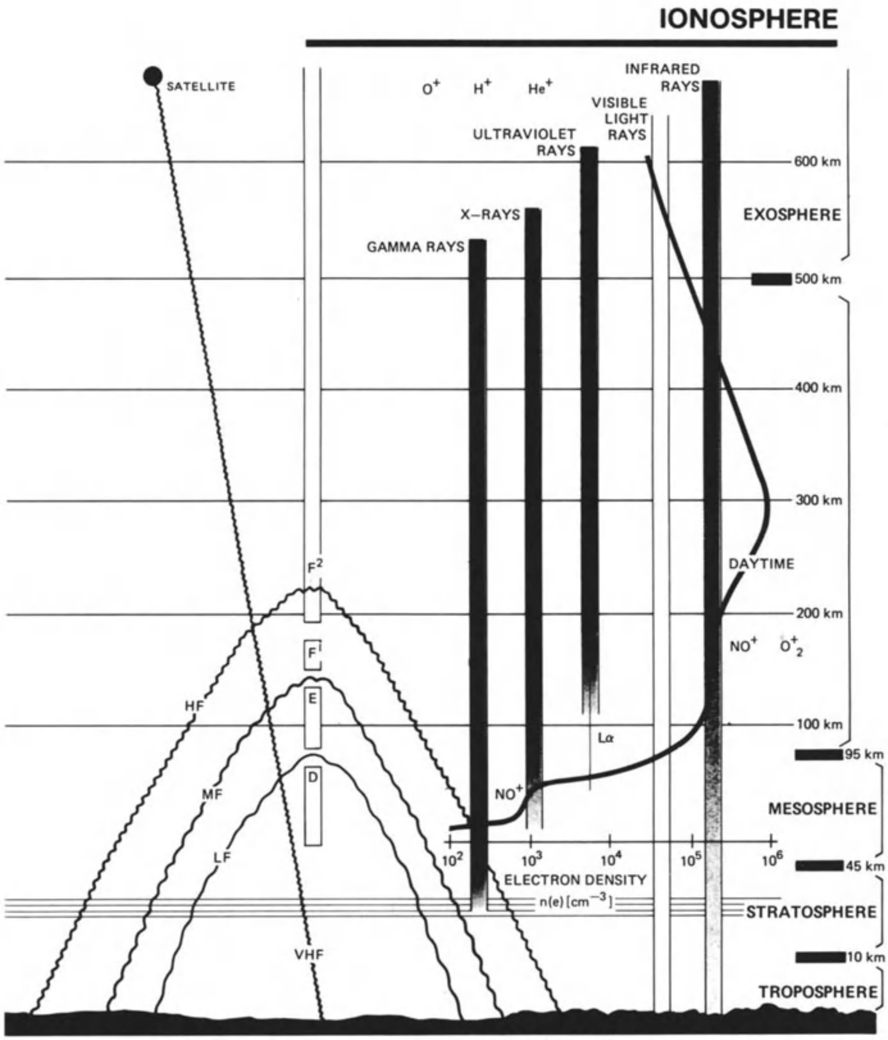


Fig. 1.3. Idealized representation of daytime ionospheric electron density distribution

◄

Fig. 1.1. Portion of the EM spectrum useful for ionospheric probing

Fig. 1.2. Schematic representation of the earth's atmosphere under idealized conditions. (NRC Report Solar-Terrestrial Research for the 1980's. National Academy Press, 1985)

Table 1.1. Typical properties of various ionospheric regions

<table>
<tr><th rowspan="3">Parameter</th><th colspan="2">D-Region</th><th colspan="2">E-Region</th><th colspan="6">F-Region</th></tr>
<tr><th colspan="2">60 km</th><th colspan="2">100 km</th><th colspan="2">200 km</th><th colspan="2">300 km</th><th colspan="2">500 km</th></tr>
<tr><th>Day</th><th>Night</th><th>Day</th><th>Night</th><th>Day</th><th>Night</th><th>Day</th><th>Night</th><th>Day</th><th>Night</th></tr>
<tr><td>Neutral concentration (m^{-3})</td><td colspan="2">7.2×10^{21}</td><td colspan="2">1.2×10^{19}</td><td colspan="2">7.6×10^{15}</td><td>9.8×10^{14}</td><td>6.6×10^{14}</td><td colspan="2">6.0×10^{13}</td></tr>
<tr><td>Electron concentration (m^{-3})</td><td colspan="2">10^{6}</td><td>1.7×10^{11}</td><td>10^{10}</td><td>3.5×10^{11}</td><td>3×10^{10}</td><td>1.1×10^{12}</td><td>3.5×10^{11}</td><td colspan="2">$\sim 10^{10}$</td></tr>
<tr><td>Gas temperature (K)</td><td colspan="2">250</td><td colspan="2">210</td><td colspan="2">1100</td><td>1360</td><td>980</td><td colspan="2">1600</td></tr>
<tr><td>Ion-neutral collision freq. (s^{-1}) ν</td><td colspan="2">6×10^{6}</td><td colspan="2">7.6×10^{3}</td><td colspan="2">5</td><td colspan="2">0.75</td><td colspan="2">6×10^{-2}</td></tr>
<tr><td>Electron-neutral collision freq. (s^{-1}) ν</td><td colspan="2">4×10^{7}</td><td>48,000</td><td>42,000</td><td>150</td><td>100</td><td>18</td><td>7</td><td>0.9</td><td>0.16</td></tr>
<tr><td>Ion gyro frequency (rad s^{-1}) Ω</td><td colspan="2">~ 140</td><td colspan="2">100</td><td colspan="2">100</td><td colspan="2">210</td><td colspan="2">190</td></tr>
<tr><td>Electron gyro frequency (rad s^{-1}) Ω</td><td colspan="2">8.5×10^{6}</td><td colspan="2">8.4×10^{6}</td><td colspan="2">8.0×10^{4}</td><td colspan="2">7.6×10^{6}</td><td colspan="2">7.0×10^{6}</td></tr>
<tr><td>Scale height (km) H</td><td colspan="2">7.5</td><td colspan="2">6.3</td><td colspan="2">37.0</td><td colspan="2">54.7</td><td colspan="2">73.5</td></tr>
</table>

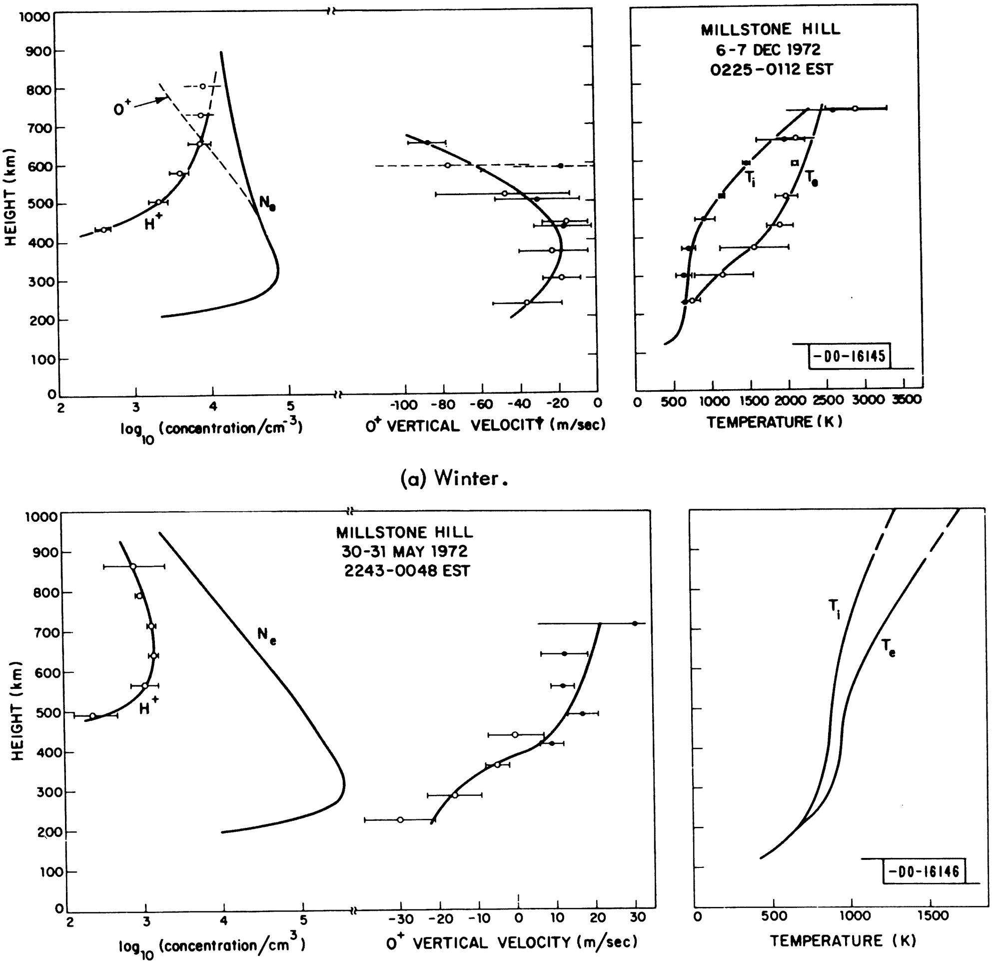
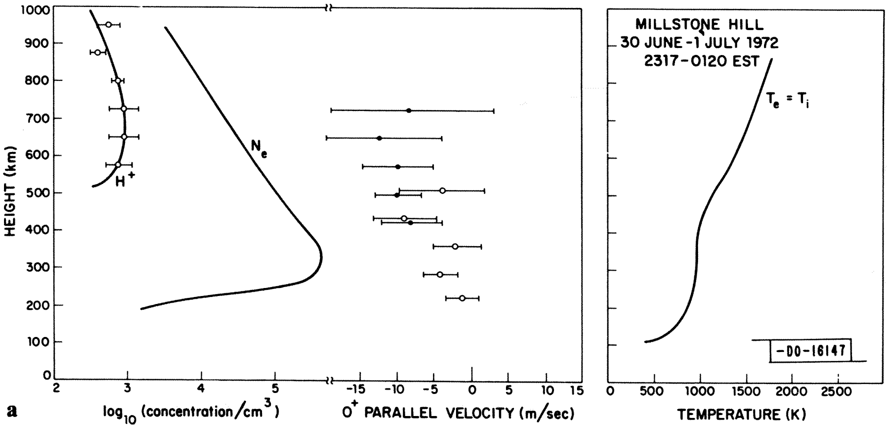


Fig. 1.4. Examples of electron density and temperature distribution – Millstone Hill winter from the Millstone incoherent scatter radar (ISR). (Evans 1979)

Ionospheric properties vary markedly with geographic and geomagnetic coordinates, local time, height, season sunspot cycle, and geomagnetic stormtime. Phenomena such as tides, thermospheric winds, and traveling ionospheric disturbances (TID's) also distribute some of the energy deposited at high latitudes equatorward, thus modifying the mid-latitude ionospheric structure. Therefore, the properties shown in Fig. 1.3 and Table 1.1 represent only "typical" values. Some idea of the extremes in variation of one ionospheric characteristic – the electron density profile – is shown in Figs. 1.4 through 1.13, and a summary of some temporal changes in the high latitude ionosphere is illustrated in Table 1.2. The *electron density profile* was chosen by the author to be representative of ionospheric structure because it was available from equatorial, mid-latitude auroral, and polar latitude incoherent scatter radars.



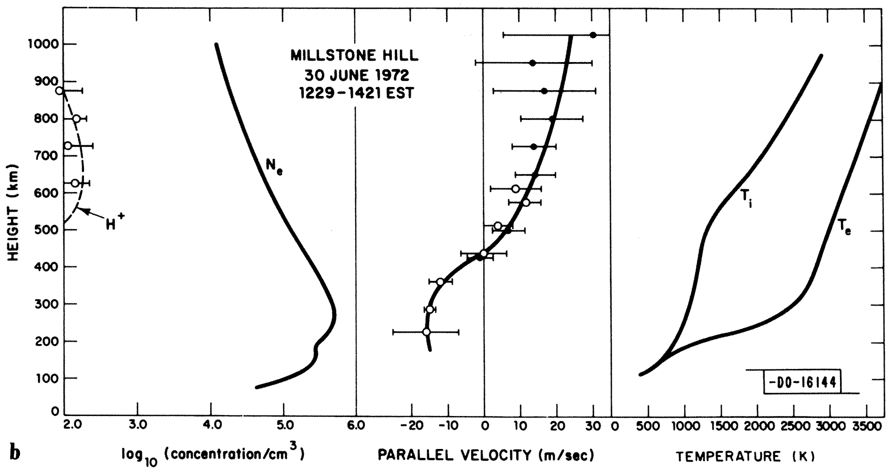


Fig. 1.5. a Example of electron density and temperature distribution – Millstone Hill, midsummer. (Courtesy of John Foster) **b** Example of electron density, parallel ion velocity, and temperature at Millstone Hill for midsummer afternoon conditions. (Courtesy to John Foster)

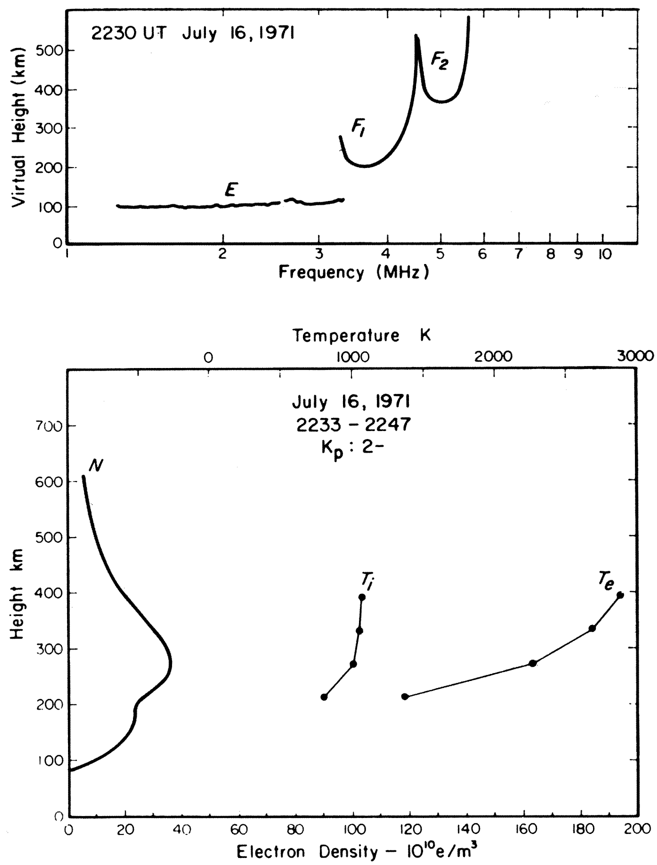


Fig. 1.6. Simultaneous profiles from the Chatanika ISR and College, Alaska, ionograms for midsummer magnetically quiet afternoon conditions (Bates and Hunsucker 1974). System height resolution was 50 km